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I also certify that by virtue of an assignment registered under the Patents Act 1977, the application is now proceeding in the name as substituted.

I also certify that the attached copy of the request for grant of a Patent (Form 1/77) bears an amendment, effected by this office, following a request by the applicant and agreed to by the Comptroller-General.

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Signed [signature] Evans.

Dated - 7 JUN 2000

GB9906361.2

By virtue of a direction given under Section 30 of the Patents Act 1977, the application is proceeding in the name of

Incorporated in the United Kingdom
MARCONI CASWELL LTD
One Bruton Street
LONDON
IX 8AQ
United Kingdom

Incorporated in the United Kingdom

[ADP No. 07806326001]

Patents Form 1/77

Patents Act 1977
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1/77

22MAR99 E434064-1 C06256
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Request for grant of a patent

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1. Your reference — **P/61761.GBA** — 19 MAR 1999

2. Patent application number *(The Patent Office will fill in this part)* — 19 MAR 1999 **9906361.2**

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

   Marconi Electronic Systems Ltd
   The Grove
   Warren Lane
   Stanmore
   Middx HA7 7LT

   SECTION 30 (1977 ACT) APPLICATION FILED 27.01.00.

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   Patents ADP number *(if you know it)* — 40527004

   If the applicant is a corporate body, give the country/state of its incorporation — **ENGLAND** 7524066001

4. Title of the invention

   INTENSITY-WAVELENGTH CODED FIBRE BRAGG GRATING SENSORS

5. Name of your agent *(if you have one)*

   "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

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6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number — Country — ing year)

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8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
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Claim(s)	5
Abstract	1
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Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature C F Hoste
C F HOSTE

Date
19th March 1999

12. Name and daytime telephone number of person to contact in the United Kingdom — Ian Collier — 01245 275125

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STRAIN SENSING

This invention relates to strain sensing and more especially to a strain sensor, apparatus for use with and a method of operating a strain sensor for sensing structural health and load monitoring.

Structural health and load monitoring of structures such as bridges and buildings is well known. Typically such systems measure the tensile or compressive strain within the structure, that is the change of length (extension or contraction) relative to the original length, which is indicative of the loading of the structure. Such information can be used in assessing damage and warning of impending weakness in the structural integrity of structures such as aircraft, space platforms, marine vessels, bridges and other structures as well as in their engineering design.

To measure strain within such structures it is known to use a strain sensor. Early strain sensors relied on a change in electrical resistance with strain and typically comprised four terminal devices in which two terminals were used to apply electrical current to the device and the other two for accurately sensing the potential difference developed across it. A particular disadvantage of such electrical resistance sensors is that when it is required to measure strain at a large number of points, as would be the case in structural monitoring of structures such as bridges and buildings, such sensors require a very large number of electrical connections, making them cumbersome and prone to electrical failure.

More recently optical fibre strain sensors have been proposed which overcome a number of the problems of electrical resistance sensors. Optical fibre strain sensors comprise an optical fibre containing a number of components which are responsive to applied strain. Such components can comprise birefringent elements, micro-bends, Fabry-Perot resonators or intra-core Bragg gratings. In the case of the latter which are often termed fibre Bragg gratings, each Bragg grating which itself constitutes a respective strain sensor, reflects light at a characteristic wavelength which is determined by the pitch of the grating. This characteristic wavelength will change if the optical fibre is subjected to tensile or compressional strain which affects the pitch of the grating. Strain is measured by measuring a change in the characteristic wavelength of each grating. By providing a number of gratings along the length of the fibre, each of which reflects light at a different characteristic wavelength, it is possible to measure strain at a number of different points along the optical fibre.

Optical fibre strain sensors offer a number of advantages compared to electrical strain sensing techniques, making them attractive for structural health monitoring applications. For example, the Bragg grating characteristic wavelength is a linear function of change in grating pitch; fibre Bragg gratings are inherently wavelength encoded and consequently problems of intensity magnitude variation are eliminated, being fully integrated within the optical fibre eliminates any point of mechanical weakness, they are immune to electro-magnetic interference (EMI), are lightweight, resistant to corrosion and fatigue, inherently safe in that they cannot initiate fires or explosions and are compatible with fibre reinforced materials. In relation to the latter

their compatibility has lead to the emergence of so-called "smart structures" which structurally integrate optical fibre sensors thereby enabling continual monitoring of the internal strain of the structure and/or any load to which it is subjected.

Whilst optical fibre strain sensing is found to be effective the inventors have appreciated that it suffers from certain limitations. Fibre Bragg gratings can be addressed in the wavelength, time and space domains. The number of fibre Bragg grating sensors that can be integrated into a single fibre and addressed by wavelength multiplexing is limited which is a consequence of the limited spectral range of the optical sources which are used to operate such sensor systems. Typically, the spectral range of the currently available optical sources is 30 to 40 nm and it is usually required to be able to measure strains in the region of 3,000 to 5000 $\mu\varepsilon$ (that is a 0.3% - 0.5% mechanical extension/contraction) which corresponds to a change in the characteristic wavelength of between 3 to 5 nm. In order to effectively operate a number of Bragg grating sensors within a single optical fibre it is necessary to dedicate a well defined wavelength range to each sensor to ensure that at its maximum wavelength change the characteristic wavelength of any given sensor cannot intrude upon the wavelength range of the sensor in the adjacent wavelength band since, under these conditions, it is impossible to discriminate between light reflected from the two sensors. As a result the number of gratings that can be incorporated in a single fibre is limited.

The present invention has arisen in an endeavour to overcome at least in part the limitations of the known strain sensing arrangements.

According to the present invention a strain sensor comprises an optical waveguide having a plurality of reflecting structures along its length, wherein each structure reflects light at a different characteristic wavelength which changes in dependence on a change of physical length of at least part of the reflecting structure; characterised in that the reflectivity of reflecting structures which reflect at characteristic wavelengths which are adjacent to each other are configured to be different such that the intensity of light reflected from adjacent structures can be used to discriminate between them. Since discrimination between the reflection characteristics of structures which are adjacent in wavelength is based on the relative magnitude of their reflectivities, this allows reflecting structures to have overlapping wavelength bands thereby enabling more reflecting structures to be incorporated within an optical waveguide for a given optical spectral range.

By securing the regions of the optical waveguide which include the reflecting structures, to an object, any change in length of the object will cause a change in the length of the reflecting structure which will be detected as a change in the characteristic wavelength. Furthermore, if these regions of the optical waveguide are placed in thermal contact with an object, any change in temperature will cause a change in the physical length of the reflecting structure which will be detected as a change in characteristic wavelength and the strain sensor of the present invention thus acts as an effective temperature sensor. It will be appreciated that in both measuring strain and temperature the strain sensor measures a change in the length of at least a part of the reflecting structure, that is it measures an internal strain of the sensor. In

the context of the present invention the term strain sensor is intended to be construed broadly as a sensor which relies on a change in length and should not be restricted to a sensor which is for measuring strain in an object to which it is attached.

Advantageously the reflecting structures which reflect at adjacent wavelengths are configured such that one structure reflects light at one characteristic wavelength and the structure adjacent in wavelength is selected to reflect light at two characteristic wavelengths. Preferably the reflecting structure which reflects light at two characteristic wavelengths is configured such that the two wavelengths are separated by at least the width of the reflection characteristic of the structure which reflects at the adjacent wavelength. Such an arrangement is particularly advantageous since at least one of the pair of characteristic wavelengths always remains resolvable and therefore discrimination between the reflecting structures is possible.

Most conveniently the optical waveguide comprises an optical fibre and preferably the or each reflecting structure comprises a grating structure, most preferably a Bragg grating, in which a change in the characteristic wavelength is in consequence of a change in the pitch of the grating. In a preferred implementation the optical fibre includes a photo refractive dopant, such as for example a silica optical fibre doped with germanium oxide, and the or each grating structure is optically written into the fibre core by, for example, exposing the fibre to ultra-violet (UV) holographic projection. In such a case the spacing of the fringes of the holographic projection determines the pitch and hence the characteristic wavelength of the grating and the

intensity of the UV light determines the reflectivity at the characteristic wavelength.

According to a second aspect of the invention an apparatus for measuring strain comprises a strain sensor described above; a light source operable to apply light to the waveguide of the sensor, said light having a wavelength range which covers at least the range of wavelengths over which the reflecting structures reflect and detector means for determining the change of characteristic wavelength at which each reflecting structure reflects light, said changes being indicative of a change in length of at least a part of the respective reflecting structure.

Preferably the detector means determines the changes in characteristic wavelength by measuring the wavelengths at which the sensor reflects light. Since the strain sensor only reflects light at various characteristic wavelengths, any light which is not reflected will pass along the optical waveguide substantially unattenuated. As a result, at the far end of the waveguide the changes in wavelength will appear as a change in attenuation of transmitted light. In an alternative arrangement the detector means measures light transmitted by the sensor and determines the changes by measuring the changes in wavelength at which light transmission is attenuated.

In a particularly preferred form of apparatus the detector means further comprises means for utilising the relative magnitude of the intensity of the reflected light or the relative magnitude of the intensity at which light transmission is attenuated to discriminate between reflecting structures which are adjacent in wavelength.

According to yet a further aspect of the invention a method of measuring strain comprises providing a strain sensor described above; applying light to the waveguide of the sensor, said light having a wavelength range which covers at least the range of wavelengths over which the reflecting structure reflects light, and detecting any change in the characteristic wavelength at which the reflecting structures reflect light. Preferably the changes in characteristic wavelength are detected by measuring the wavelengths at which the sensor reflects light.

Alternatively the changes in characteristic wavelength can be detected by measuring the wavelengths at which the transmission of light through the sensor is attenuated.

Preferably the method further comprises detecting the relative magnitude of the intensity of reflected light or the relative magnitude of the intensity at which transmitted light is attenuated to discriminate between reflecting structures which are adjacent in wavelength.

When it is desired to measure strain within an object the method further comprises securing a part of the waveguide having at least a part of one of the reflecting structures to the object such that a change in the physical length of the object causes a change in the physical length of the reflecting structure. Alternatively, or in addition, when it is desired to measure the temperature of an object, the method further comprises placing a part of the waveguide having at least a part of one of the reflecting structures in thermal contact with the object such that a change in the temperature of

the object causes a change in the physical length of at least a part of the reflecting structure.

In order that the invention may be better understood a strain sensor and apparatus in accordance with the invention for measuring strain and/or temperature will now be described by way of example only with reference to the accompanying drawings in which:

Figure 1 is a schematic of a strain and/or temperature sensing apparatus in accordance with the invention;

Figure 2(a) is a series of plots of measured reflectivity I versus wavelength for different applied strains for the apparatus of Figure 1;

Figure 2(b) is a plot of the measured wavelength shift $\Delta\lambda$ of the peak (x) of Figure 2(a) versus strain;

Figure 3(a) is a series of plots of measured reflectivity I versus wavelength for a further strain sensor for different applied strains; and

Figure 3(b) is a plot of the measured wavelength shift $\Delta\lambda$ for the two peaks (x,y) of Figure 3(a) versus strain.

Referring to Figure 1 a strain sensing apparatus comprises a broad band light source 2, a tunable filter 4, an optical fibre strain sensor 6, a directional coupler 8, two photodiodes 10 and 12 respectively, a mixer circuit 14 and a processor 16. The optical fibre strain sensor 6, which is a key aspect of the present invention and considered inventive in its own right, comprises a silica optical fibre which is doped germanium oxide. Spaced along the length of the optical fibre there are provided within the core of the optical fibre a plurality of Bragg diffraction gratings. Each grating is produced within the core of the optical fibre by exposing the core of the fibre to ultra-violet (UV) light using holographic exposure, though other techniques such as a phase mask or point by point writing can be used. Germanium oxide is a photo refractive dopant which when exposed to UV light results in a permanent change of refractive index and hence a Bragg diffraction grating can be defined within the core by exposing the core to an appropriate pattern of UV light. Each grating structure within the fibre is selected to have a characteristic wavelength, denoted λ_1 to λ_{n+1} in Figure 1, which is determined by the pitch of the respective grating. The method of producing optical fibre gratings using holographic projection is known and is for example described in an article by one of the inventors in the GEC Journal of Technology Volume 15 Number 1, 1998, paragraph 2.3, which is hereby incorporated by way of reference thereto.

The gratings which reflect at adjacent wavelengths, for example λ_1 and λ_2 or λ_n and λ_{n+1} in Figure 1 are arranged to alternately have reflectivities of 50 and 95% respectively which will hereinafter be referred to as "low" and "high" reflectivity.

Using the fabrication technique described this difference in reflectivity is achieved by altering the intensity of the UV light used to expose and so define the grating structure within the fibre. As will become apparent the absolute reflectivity of gratings which are adjacent in wavelength is not critical and the use of 50 and 95% are exemplary only. The important criterion is that the relative reflectivity of gratings which are adjacent in wavelength have sufficiently different reflectivities to enable discrimination between light reflected from the respective gratings. The optical fibre sensor 6 further comprises associated with each grating region mechanical securing means to enable the fibre to be mechanically secured to an object whose strain is to be measured. Such mechanical securing means can comprise an encapsulating tube, flanges or mounting brackets made of metal, glass or a plastics material, to which the fibre is connected either by adhesive or by mechanical clamping.

The broad band light source 2, which conveniently comprises a light emitting diode or Erbium doped fibre amplifier, is operable to produce a continuous broad band light output over the wavelength range 1550 nm $\pm$ 30 nm. This continuous light output is applied to the wavelength selective filter 4, which can comprise for example an acousto-optic tuneable filter or a scanned Fabry-Perot filter, such that the filter produces an optical output which is swept over the range of wavelengths of the broad band source 2. In an alternative arrangement the light source 2 and tuneable filter 4 can be replaced with a suitable optical source which is tuneable in the wavelength domain such as for example a tuneable laser diode. The swept light output is applied to the first input of the directional coupler 8 which splits the light such that half passes

into and along the optical fibre sensor 6 and the other half passes to the first photodiode 10. Light which is reflected by the Bragg gratings in the optical fibre sensor 6 travels back toward the directional coupler 8 where it is split such that half passes to the second photodiode 12 and the remaining half towards the wavelength selective filter 4. The light which is not reflected by the optical fibre sensor 6 passes along the length of the optical fibre and is dissipated in a light dump 18 at the far end of the optical fibre.

The outputs from the respective photodiodes 10 and 12 are applied to the mixing circuit 14 such that the output represents the ratio of reflected light from the optical sensor 6 at a given wavelength relative to the intensity of light applied to the sensor at that wavelength. As the tunable filter 4 scans over the wavelength bandwidth of the light source 2 the output from the mixer 14 represents the reflection spectrum of the sensor 6 which has been normalised relative to the light applied to it and this spectrum is detected by the processor 16 which preferably comprises a spectrum analyser. It is preferable, though not essential, to normalise the reflection spectrum as described since the source 2 is unlikely to produce a uniform light intensity output over its full spectral range.

Referring to Figure 2(a) there are shown the reflection intensity I profiles for a pair of "low" and "high" reflectivity gratings which are adjacent in wavelength versus wavelength for increasing amounts of applied tensile strain to the "low" reflectivity grating. These test data are for a sensor having an array of Bragg gratings having a

2nm spectral spacing and a typical grating bandwidth of ≈ 0.4nm. The "high" (95%) reflectivity grating was kept strain free whilst the "low" (50%) reflectivity grating was strained in steps of $80\mu\varepsilon$ up to $4000\mu\varepsilon$, which corresponds to a 4nm change in wavelength.

Starting with the uppermost profile, which shows the sensor when no tensile strain is applied, it will be seen that the "low" reflectivity grating reflects light at a lower characteristic wavelength and the reflection peak is denoted "x" in the Figure. As tensile strain is applied to the "low" reflectivity grating, this causes an increase in the grating spacing, which causes the characteristic wavelength of the reflectivity peak x to increase and the peak moves toward and through the peak of the "high" reflectivity grating. For clarity, it should be noted that in this example no strain is applied to the "high" reflectivity grating and hence the characteristic wavelength of its reflectivity peak remains constant.

Figure 2(b) is a plot of the wavelength shift $\Delta\lambda$ of the reflectivity peak x versus applied tensile strain. As will be seen from this Figure, the change in wavelength $\Delta\lambda$ is a linear function of applied strain and includes a band over which strain cannot be measured; this is denoted by arrows "AA" in the Figure. In this band the reflection peaks from the "low" and "high" reflectivity gratings cannot be discriminated because they spectrally overlap, as illustrated in the middle profile of Figure 2(a). In spite of this band, whose width is approximately 500 $\mu\varepsilon$, it is still possible to double the number of gratings within a given spectral range.

In the known systems the number of gratings (n) that can be incorporated into a single fibre is determined by $n \approx \Delta\lambda_{SR}/\Delta\lambda_{BG}$ where $\Delta\lambda_{SR}$ is the spectral range of the light source and $\Delta\lambda_{BG}$ is the spectral bandwidth of each fibre Bragg grating. The spectral bandwidth $\Delta\lambda_{BG}$ is necessary to ensure that reflection peaks for adjacent gratings do not cross each other. In contrast to the known sensors, the sensor of the present invention additionally encodes the reflectivity of adjacent gratings which enables discrimination of the light reflected from the respective gratings. As a result in the spectral spacing necessary between adjacent gratings is approximately halved, though the strain sensing spectral bandwidth for each grating is still $\Delta\lambda_{BG}$. The total number of gratings that can be incorporated within the fibre for a given spectral range is thus doubled.

As described above, there is a band AA in which the two gratings spectrally overlap and this band can be minimised by using narrow spectral response gratings. However, narrow spectral response gratings will reflect less light, which will degrade the signal to noise ratio in the system. To minimise the effect of the overlapping region without the need to use ultra-narrow spectral response gratings, it is proposed in a further sensor according to the invention to replace the "low" reflectivity grating with one which is still of "low" reflectivity but reflects at two characteristic wavelengths. The spacing of the two characteristic wavelengths is selected to be at least as large as the bandwidth of the high reflectivity grating.

Referring to Figure 3, this shows for such a sensor (a) a series of plots of measured

reflectivity I versus wavelength for different applied strains to the "low" reflectivity grating and (b) a plot of the measured wavelength shift $\Delta\lambda$ for the reflection peaks x,y of the low reflectivity grating versus applied strain. Referring to Figure 3(a) it will be seen that as the "low" reflectivity grating is subjected to strain the pair of reflectivity peaks (x,y) both shift at the same rate such that even when the spectral responses of the two gratings overlap at least one of the pair of peaks is always resolvable. Figure 3(b) shows the wavelength shift for both peaks (x,y) for the dual peak response as crosses and circles, respectively, versus applied strain. It will be seen that when information concerning both peaks of the dual peak response is considered the band AA over which strain cannot be measured is substantially reduced. The remaining small band is due to the relatively broad bandwidth of the high reflectivity grating. Further tests have shown that the gap is virtually eliminated if the spacing of the dual peaks is increased or if the bandwidth of the high reflectivity peak can be reduced.

It will be appreciated that the present invention is not restricted to the specific embodiment described and that variations can be made which are within the scope of the invention. For example, in the apparatus described the intensity of the light reflected from the sensor is measured. In other embodiments it is envisaged to measure the light transmitted by the optical fibre, since the absorption loss in the fibre is negligible. Consequently, the sum of transmitted light and reflected light is substantially unity and the change in characteristic wavelength of the Bragg gratings can be determined by measuring the change in wavelength at which the fibre attenuates transmitted light. It will be further appreciated that the invention is not

limited to Bragg gratings, and other forms of reflecting structures can be used provided their characteristic wavelength is affected by a change in the physical length of the structure. Although the sensor is conveniently formed as an optical fibre other forms of optical waveguide could be used though they are likely to be less convenient.

The operation of the strain sensor has been described by way of example to strain sensing within an object. It will be appreciated that the said strain sensor and apparatus can also be used to measure temperature, since a change in temperature of the grating will cause an expansion or contraction of the grating and so change the grating pitch. In such an application the optical fibre is placed in thermal contact, with the object rather than being secured to it.

CLAIMS

1. A strain sensor comprising: an optical waveguide having a plurality of reflecting structures along its length, wherein each structure reflects light at a different characteristic wavelength which changes in dependence on a change of physical length of at least part of the reflecting structure; characterised in that the reflectivity of reflecting structures which reflect at characteristic wavelengths which are adjacent to each other are configured to be different such that the intensity of light reflected from adjacent structures can be used to discriminate between them.

2. A strain sensor according to Claim 1 in which the reflecting structures which reflect at adjacent wavelengths are configured such that one structure reflects light at one characteristic wavelength and the structure adjacent in wavelength is selected to reflect light at two characteristic wavelengths.

3. A strain sensor according to Claim 2 in which the reflecting structure which reflects light at two wavelengths is configured such that the two characteristic wavelengths are separated by at least the width of the reflection characteristic of the structure which reflects at the adjacent wavelength.

4. A strain sensor according to any preceding claim in which the optical waveguide comprises an optical fibre.

5. A strain sensor according to any preceding claim in which the or each reflecting structure comprises a grating structure and wherein the change in characteristic wavelength is in consequence of a change in the pitch of the grating.

6. A strain sensor according to Claim 5 in which the or each grating structure comprises a Bragg grating.

7. A strain sensor according to Claim 5 or 6 when dependent on Claim 4 in which the optical fibre includes a photo refractive dopant and the or each grating structure is optically written into the fibre.

8. A strain sensor according to Claim 7 in which the optical fibre comprises silica doped with germanium oxide.

9. A strain sensor substantially as hereinbefore described or substantially as illustrated by way of reference to the Figure 1 of Figure 2 or Figure 3 of the accompanying drawings.

10. Apparatus for measuring strain; comprising a sensor according to any preceding claim, a light source operable to apply light to the waveguide of the sensor, said light having a wavelength range which covers at least the range of

wavelengths over which the reflecting structures reflect and detector means for determining the change of characteristic wavelength at which the reflecting structures reflect light, said changes being indicative of a change in length of at least a part of the respective reflecting structure.

11. Apparatus for measuring strain according to Claim 10 in which the detector means determines the change in characteristic wavelength by measuring the wavelengths at which the sensor reflects light.

12. Apparatus for measuring strain according to Claim 10 in which the detector means measures light transmitted by the sensor and determines the change in characteristic wavelength by measuring the changes in wavelength at which light transmission is attenuated.

13. Apparatus according to any one of Claims 10 to 12 in which the detector means further comprises means for utilising the relative magnitude of the intensity of reflected light or the relative magnitude of the intensity at which light transmission is attenuated to discriminate between reflecting structures which are adjacent in wavelength.

14. An apparatus for measuring strain substantially as hereinbefore described or substantially as illustrated by way of reference to the Figure 1 of the accompanying drawings.

15. A method of measuring strain comprising; providing a sensor according to any one of Claims 1 to 8, applying light to the waveguide of the sensor, said light having a wavelength range which covers at least the range of wavelengths over which the reflecting structure reflects light, and detecting any change in the characteristic wavelength at which the reflecting structures reflect light.

16. A method according to Claim 15 comprising detecting the change in characteristic wavelength by measuring the wavelengths at which the sensor reflects light.

17. A method according to Claim 15 comprising detecting the change in characteristic wavelength by measuring the wavelengths at which the transmission of light through the sensor is attenuated.

18. A method according to Claim 16 or Claim 17 and further comprising detecting the relative magnitude of the intensity of reflected light or the relative magnitude of the intensity at which transmitted light is attenuated to discriminate between reflecting structures which are adjacent in wavelength.

19. A method according to any one of Claims 15 to 18 and further comprising sweeping the wavelength of the light applied to the sensor.

20. A method according to any one of Claims 15 to 19 in which, when it is desired to measure strain within an object, further comprises securing a part of the waveguide having at least a part of one of the reflecting structures to the object such that a change in the physical length of at least a part of the object causes a change in the physical length of at least a part of the reflecting structure.

21. A method according to any one of Claims 15 to 19 in which, when it is desired to measure the temperature of an object, further comprises placing a part of the waveguide having at least a part of one of the reflecting structures in thermal contact with the object such that a change in the temperature of the object causes a change in the physical length of at least a part of the reflecting structure.

22. A method of strain sensing substantially as hereinbefore described.

ABSTRACT

A strain sensor comprises an optical waveguide (6) having a plurality of reflecting structures (Bragg gratings) along its length. Each structure reflects light at a different characteristic wavelength (λ_1 to λ_{n+1}) which changes in dependence on a change of physical length of at least part of the reflecting structure. The reflectivity of reflecting structures which reflect at characteristic wavelengths which are adjacent to each other (λ_1 and λ_2 or λ_n or λ_{n+1}) are configured to be different such that the intensity of light reflected from adjacent structures can be used to discriminate between them.

Figure 1

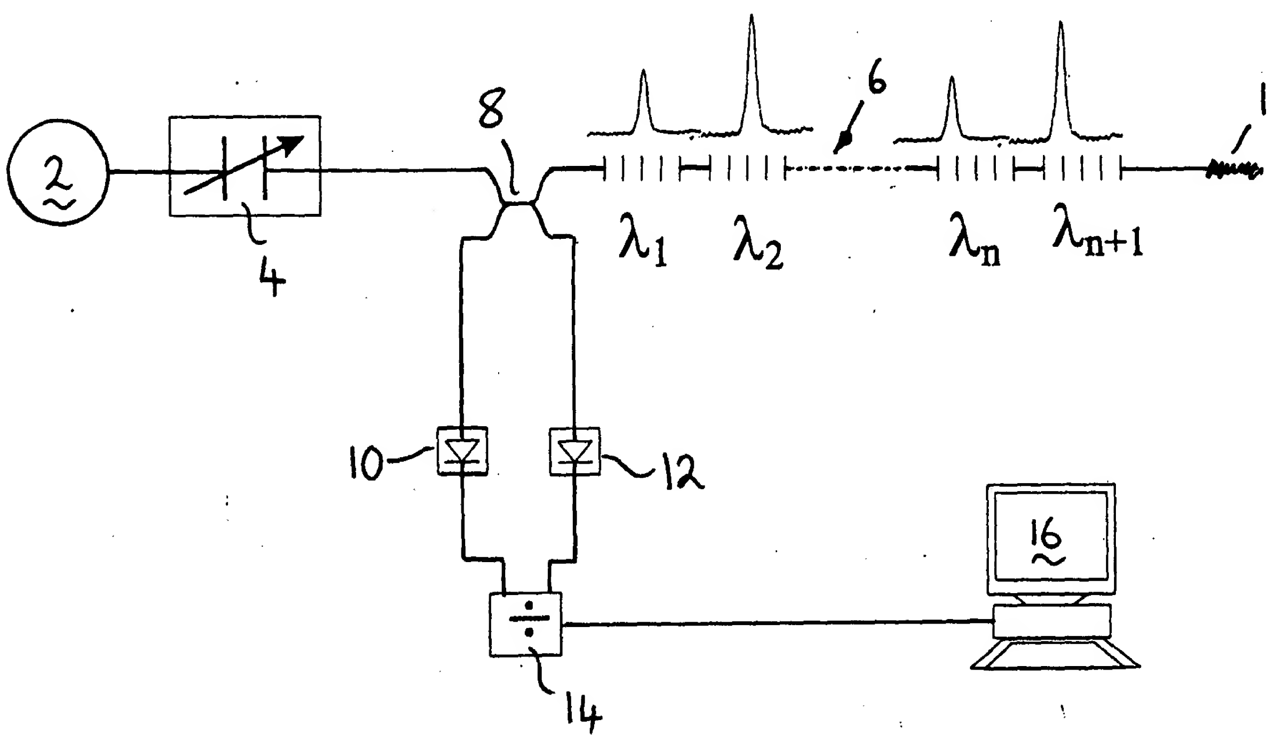

Figure 1

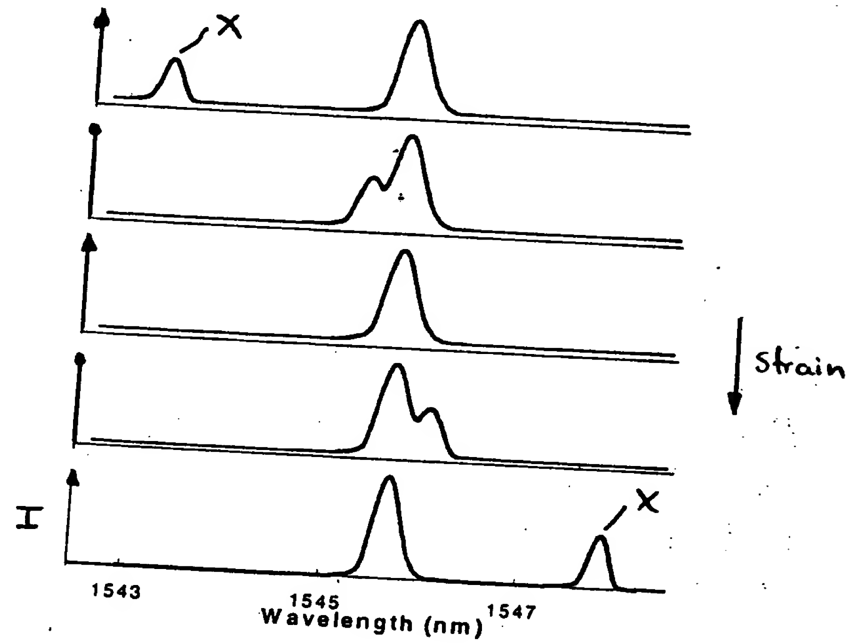

Figure 2(a)

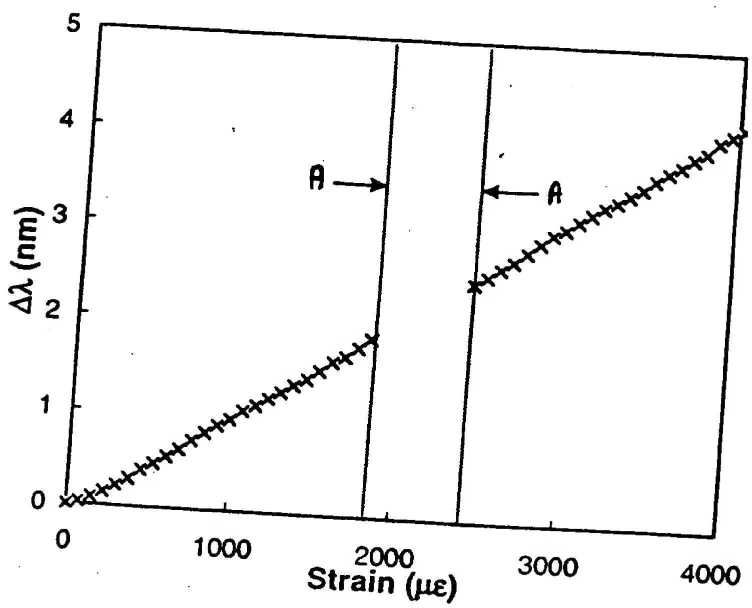

Figure 2(b)

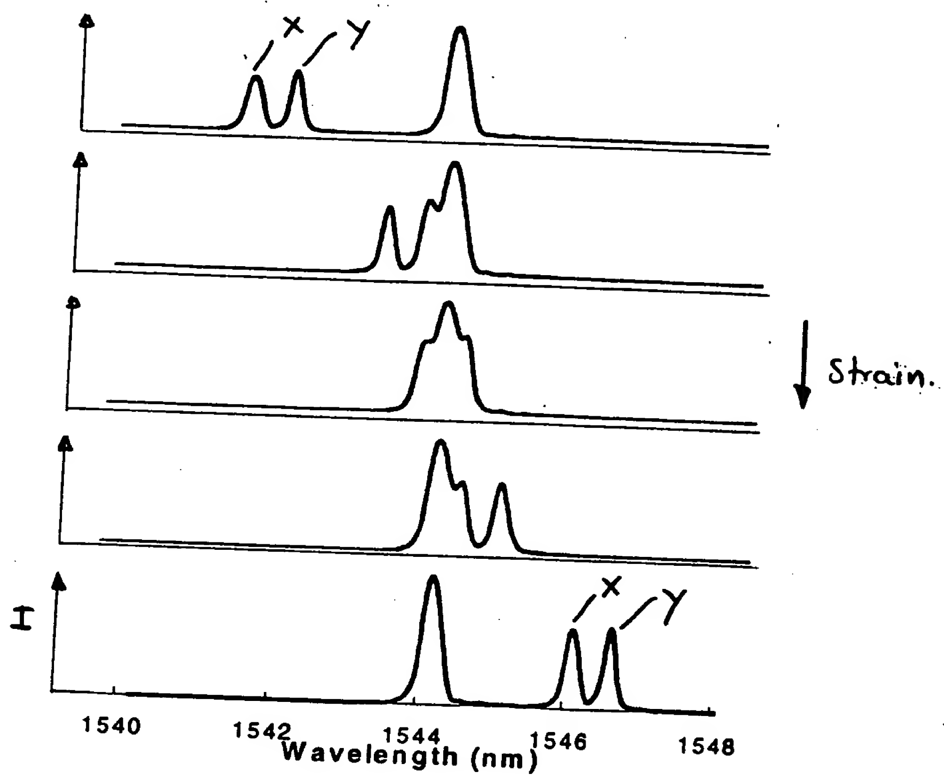

Figure 3(a)

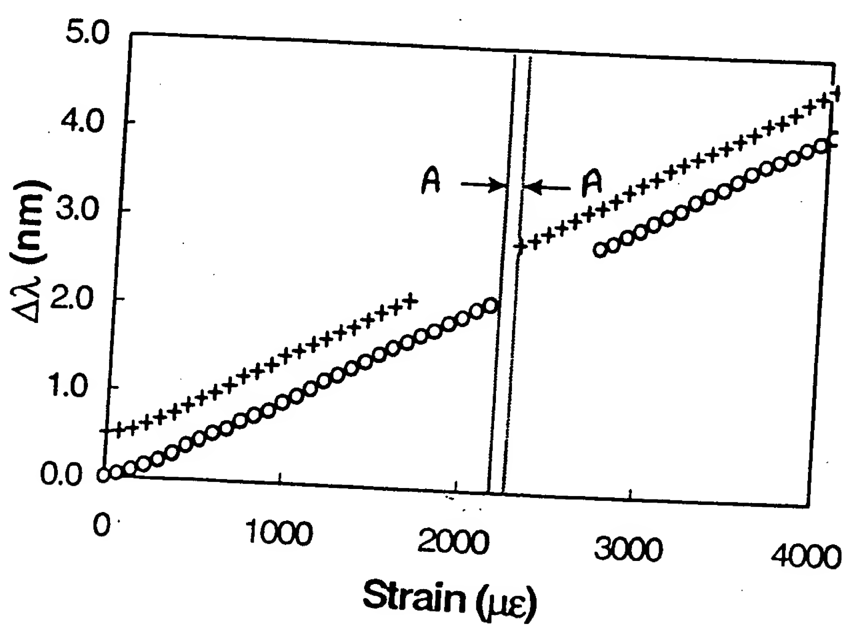

Figure 3(b)

PCT/GB 00/00994

Marconi Int Prop.

17/3/00